

IS HOLMBERG-II BEYOND MOND THEORY?

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ABSTRACT

We compare the basic properties and kinematics of two gas-rich dwarf galaxies: KK246 and Holmberg II (HoII). HoII is 20 times more luminous in the blue-band than KK246 and its H I mass is a factor of 6 higher than in KK246. However, the amplitudes of the rotation curves (at the last measured point) of both galaxies are very similar, of about 40 km s⁻¹ at a galactocentric radius of 7 kpc. This fact is challenging for modified theories of gravity that predict a one-to-one relation between gravity at any radius and the enclosed baryonic mass in galaxies. In particular, Modified Newtonian Dynamics (MOND) predicts an asymptotic flat velocity of 60 km s⁻¹ in HoII. Since the baryonic mass of HoII is dominated by the gas component, MOND overboosts its rotation speed even if the mass of the stellar disk is taken negligibly small. We conclude the rotation curve of HoII is probably inconsistent with MOND, unless the inclination and distance are both fine-tuned to very unlikely values.

Subject headings: galaxies: individual (Holmberg II) – galaxies: kinematics and dynamics – dark matter – gravitation

1. INTRODUCTION

The dynamical mass-to-light ratios M/L derived in galaxies are usually larger than the expected mass-to-light ratios of the stellar component, indicating that they must contain dark matter. Alternatively, one could argue that the discrepancy between total mass and baryonic mass could tell us that the Newtonian law of gravity is not governing the dynamics. In particular, the Modified Newtonian Dynamics (MOND) proposed by Milgrom (1983) has been proven to be successful to reproduce the kinematics of a significant fraction of spiral galaxies without any dark matter (see Sanders & McGaugh 2002 for a review; Milgrom & Sanders 2007; Sanders & Noordermeer 2007; Gentile et al. 2007). Swaters et al. (2010) report that the rotation curves of a quarter of their sample of 27 dwarf and LSB galaxies are not adequately explained by MOND. Gentile et al. (2011) also find that 3 out of 12 high-quality rotation curves from the H I Nearby Galaxy Survey (THINGS) are poorly fitted with MOND. Galaxies with poor MOND fits include NGC 2841, NGC 3198 (Bottema et al. 2002), M31 (Corbelli & Salucci 2007), M33 (Sánchez-Salcedo & Lora 2005; Corbelli & Salucci 2007), UGC 4173 (Swaters et al. 2010), UGC 6787 and UGC 11852 (Sanders & Noordermeer 2007). However, this is not necessarily a problem for MOND because of the inevitable uncertainties in the inclination and in the distance of the galaxies, and because of the presence of warps and non-circular motions.

Recently, Milgrom (2011) highlights the individual importance of the dwarf irregular galaxy KK246 as a new test, and conclude that the amplitude of its rotation curve is correctly predicted using the MOND prescription. He argues that it is rather puzzling for the Λ CDM paradigm to explain why galaxies select exactly the velocities predicted by MOND. In this note we discuss a counter-example. Indeed, the mass in gas of the dwarf

irregular galaxy Holmberg II (HoII) is a factor of 6 higher than the gas mass in KK246. Since stars hardly contribute to the baryonic mass in these galaxies, an analogue analysis dictates that the expected MOND amplitude of HoII rotation curve should be noticeably larger than the amplitude of KK246 rotation curve. However, the rotation curves of HoII and KK246 look very similar. In this paper we compare the properties of these galaxies and discuss the implications of these findings in more detail.

2. KK246 AND HOII: SIMILARITIES AND DIFFERENCES

KK246 (also referred to as ESO 461-036) and HoII (or DDO 50) are gas-rich dwarf galaxies with more mass in gas than in stars. Hence, the uncertainty of the stellar mass-to-light ratio in mass models is less relevant than in high surface brightness galaxies. In Table 1, we give some basic properties of HoII and KK246. It is worthwhile noting that KK246 resides within the nearby Tully void, while HoII belongs to the M81 group.

Careful analyses of H I observations of HoII have been carried out by two independent groups: Bureau & Carignan (2002) and Oh et al. (2011). Bureau & Carignan (2002) were able to infer the rotation curve until a radius of ~ 20 kpc. However, as these authors clearly stressed, the rotation curve derived is well defined for galactocentric radius $R < 10$ kpc because, for larger radii, velocities were only measured in the approaching side. Bureau & Carignan derived a dynamical mass-to-light ratio of 16. Recently, the THINGS high-resolution data have significantly reduce observational uncertainties at $R < 7$ kpc (Oh et al. 2011).

On the other hand, the dwarf irregular galaxy KK246 has been studied by Kreckel et al. (2011) with the VLA and EVLA. They discovered an extended H I disk and were able to measure its rotation curve until a galactocentric radius of 7 kpc. They have estimated a dynamical

TABLE 1
COMPARISON OF THE RELEVANT PARAMETERS OF THE TWO GALAXIES

Name	D Mpc	M_B	L_B $10^8 L_\odot$	$\langle i \rangle$ deg	M_{gas} $10^8 M_\odot$	M_{bar} $10^8 M_\odot$	$V_{\text{rot}}(7 \text{ kpc})$ km s^{-1}	References
KK246	7.83	-13.69	0.46	65°	1.5	2.0	41	Kreckel et al. (2011)
HoII	3.4	-16.87	8.7	49°	9.0	10.5	37	Walter et al. (2008) Oh et al. (2011)

Column (1): Name of the galaxy. Column (2): Distance. Column (3): Absolute B magnitude. Column (4): Total blue-band luminosity. Column (5): Average value of the inclination within a radius of 7 kpc. Column (6): Total mass in gas. Column (7): Total baryonic mass. Column (8): Rotation velocity at a galactocentric distance of 7 kpc. Column (9): References.

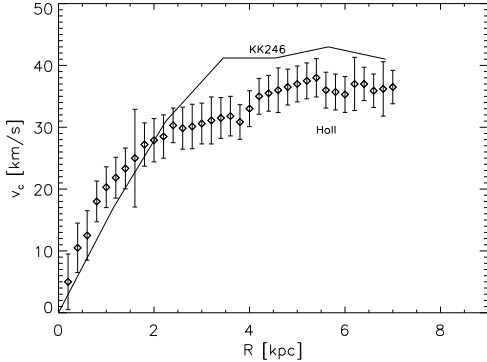


FIG. 1.— Measured rotation curves for KK246 (solid line) and HoII (symbols).

mass-to-light ratio of 89 in KK246.

In Figure 1, we plot the observed rotation curves for KK246 (Kreckel et al. 2011) and HoII (Oh et al. 2011). We see that both rotation curves are rather similar. In the case of HoII, the method of Oh et al. (2011) minimizes the effect of non-circular motions. The rotation curve of HoII was corrected for axisymmetric drift whereas this correction was not made for KK246. Axisymmetric drift corrections would cause a boost of a few km s^{-1} in the circular velocities of KK246.

3. THE BARYONIC MASS OF HOII AND KK246

In MOND framework, the rotation velocity of an isolated galaxy is determined by its visible (baryonic mass). For KK246, Kirby et al. (2008) estimated a stellar mass of $5 \times 10^7 M_\odot$, which corresponds to stellar mass-to-light ratio in the B-band of $\Upsilon_\star^B = 1.1$ in solar units (see Table 1). According to Kreckel et al. (2011), the total gas mass of KK246 is $1.5 \times 10^8 M_\odot$ (assuming that the gas mass is 1.4 times the H I mass). Therefore, the total baryonic mass of KK246 is of $2 \times 10^8 M_\odot$, as used by Milgrom (2011).

Using some relations derived from population synthesis models, Oh et al. (2011) derived the stellar mass-to-light ratio in K-band, Υ_\star^K , for HoII. With such a Υ_\star^K -value (which we will refer to as the nominal value), the stellar mass in the disk of HoII is of $1.5 \times 10^8 M_\odot$. On the other hand, Bureau & Carignan (2002) found a H I mass for this galaxy of $6.44 \times 10^8 M_\odot$, which corresponds to a total mass in gas of $9 \times 10^8 M_\odot$. Thus, the total (gas plus stars) baryonic mass in HoII is about $10.5 \times 10^8 M_\odot$, which is a factor of ~ 5 larger than the baryonic mass in KK246.

4. THE ROTATION CURVE IN MOND

The Lagrangian MOND field equations lead to a modified version of Poisson’s equation given by

$$\nabla \cdot \left[\mu \left(\frac{|\nabla \Phi|}{a_0} \right) \nabla \Phi \right] = 4\pi G \rho, \quad (1)$$

where ρ is the density, a_0 is a universal acceleration of the order of $10^{-8} \text{ cm s}^{-2}$, and $\mu(x)$ is some interpolating function with the property that $\mu(x) = x$ for $x \ll 1$ and $\mu(x) = 1$ for $x \gg 1$ (Bekenstein & Milgrom 1984). To a good approximation, the *real* acceleration at the midplane of a isolated, flattened axisymmetrical system, \mathbf{g} , is related with the Newtonian acceleration, \mathbf{g}_N , by:

$$\mu \left(\frac{|\mathbf{g}|}{a_0} \right) \mathbf{g} = \mathbf{g}_N. \quad (2)$$

The two most popular choices for the interpolating function are the “simple” μ -function, suggested by Famaey & Binney (2005),

$$\mu(x) = \frac{x}{1+x}, \quad (3)$$

and the “standard” μ -function

$$\mu(x) = \frac{x}{\sqrt{1+x^2}}, \quad (4)$$

proposed by Milgrom (1983). For a sample of galaxies having a gradual transition from the Newtonian limit in the inner regions to the MOND limit in the outer parts, Famaey et al. (2007) and Sanders & Noordermeer (2007) conclude that the plausability of the relative stellar mass-to-light ratios for bulge and disk, as well as the generally smaller global M/L , lend support to the simple μ -function (see also Weijmans et al. 2008 and Gentile et al. 2011).

Certainly HoII is not at isolation; it is embedded in the external gravitational field of M81 group. Since the modified Poisson equation is nonlinear, the internal acceleration of a system depends on the external acceleration field \mathbf{g}_{ext} (Bekenstein & Milgrom 1984). In order to quantify the external field effect (EFE), it is important to compare the internal and external accelerations. Assuming that the M81 group is bound, the external acceleration is $0.7 \times 10^{-10} \text{ cm s}^{-2}$ (Karachentsev et al. 2002). The HoII internal accelerations are of $6 \times 10^{-10} \text{ cm s}^{-2}$ and $2 \times 10^{-10} \text{ cm s}^{-2}$ at $R = 7 \text{ kpc}$ and $R = 20 \text{ kpc}$, respectively. Thus, EFE should be small at $R < 10 \text{ kpc}$. Indeed, the flatness of the rotation curve of HoII would be incompatible with HoII being dominated by the external field.

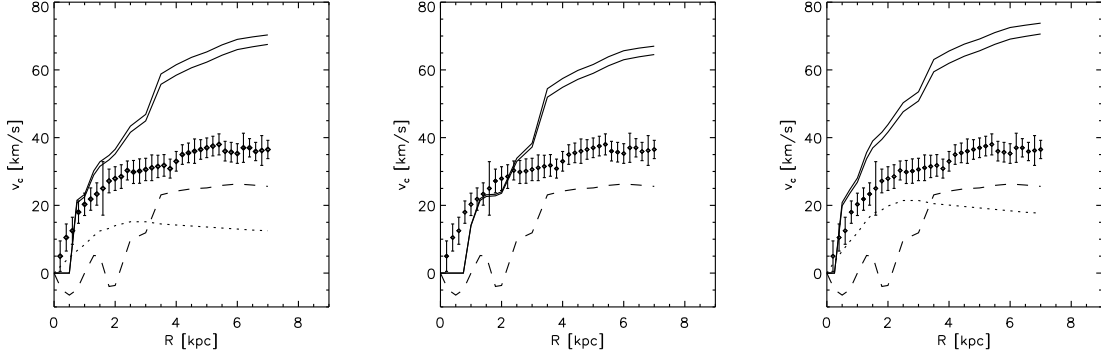


FIG. 2.— Rotation curve of HoII from Oh et al. (2011) together with the contributions of the stellar disk (dotted lines) and gas (dashed lines) for the nominal Υ_* -value (left panel), minimum disk plus gas (central panel) and twice the nominal Υ_* -value. The full lines represent the rotation curve according to MOND prescription using the simple μ -function (upper solid curves) or the standard μ -function (lower solid curves). MOND is unable to provide the amplitude of the rotation curve. Here we take $a_0 = 1.2 \times 10^{-8} \text{ cm s}^{-2}$.

In the prescription of MOND, the asymptotic velocity is $(GMa_0)^{1/4}$, where M is the total baryonic mass of the system. Consequently, the asymptotic velocity in HoII is expected to be 50% higher than in KK246. In fact, using the estimates of the baryonic masses given in Section 3 and $a_0 = 1.2 \times 10^{-8} \text{ cm s}^{-2}$, MOND predicts correctly the asymptotic velocity (42 km s^{-1}) for KK246 but overpredicts the HoII rotation speed (63 km s^{-1}). The predicted HoII rotational speed is in excess by 25 km s^{-1} .

Figure 2 shows the predicted HoII rotation curve in MOND under various Υ_*^K assumptions [the nominal value as derived by Oh et al. (2011), “minimum disk plus gas”, and twice the nominal value]. The “minimum disk plus gas” includes the gas component and uses the minimum value of Υ_* compatible with the requirement that the theoretical circular velocity must be positive and reasonably smooth (i.e. without unrealistic steep gradients within $R < 2 \text{ kpc}$). We see that the discrepancy between the observed and the predicted rotation curves is very large. The effect of varying Υ_* or the interpolating function on the MOND circular velocity at the outer disk is small. For illustration, Figure 3 shows the combined rotation curve from Bureau & Carignan (2002) and Oh et al. (2011) for the updated HoII distance of 3.4 Mpc. The shift between the observed and the theoretical rotation curves is apparent.

Using a smaller value for a_0 would help to alleviate the discrepancy. For instance, for a sample of 12 galaxies, Begeman et al. (1991) found $a_0 = (1.35 \pm 0.51) \times 10^{-8} \text{ cm s}^{-2}$. Gentile et al. (2010) obtained $a_0 = (1.22 \pm 0.33) \times 10^{-8} \text{ cm s}^{-2}$ also for a sample of 12 galaxies. However, the MOND circular rotation speed at 7 kpc for a value of a_0 at the lower end of the best-fit interval, $a_0 = 0.9 \times 10^{-8} \text{ cm s}^{-2}$, is only a few km s^{-1} slower.

In the MOND prescription, the amplitude of the rotation curve can be accounted for by adopting a distance to HoII of 1.5 Mpc and $a_0 = 0.9 \times 10^{-8} \text{ cm s}^{-2}$ (see Figure 4). Given that the uncertainty in the distance is of 0.4 Mpc (Karachentsev et al. 2002), this likely indicates that MOND cannot be made compatible with that rotation curve by a reasonable adjustment of galaxy’s distance.

A more delicate issue is the error resulting from the uncertainty in the inclination of the galaxy. It turns out

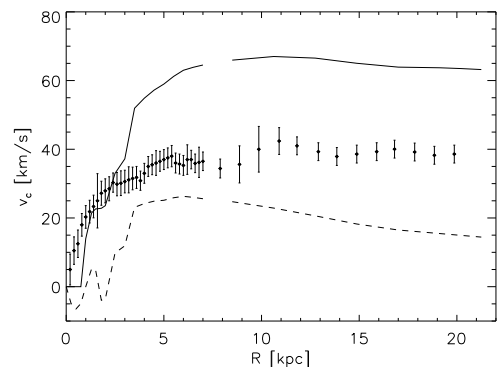


FIG. 3.— Combined rotation curve of HoII as measured by Oh et al. (2011) (at $R < 7 \text{ kpc}$) and by Bureau & Carignan (2002) at $R > 7 \text{ kpc}$. The dashed line represents the contribution to the rotation curve of the gas disk. The solid line represents the MONDian rotation curve in the “minimum disk+gas” assumption, using the standard μ -function and $a_0 = 1.2 \times 10^{-8} \text{ cm s}^{-2}$. All the variables have been rescaled for the adopted distance of $D = 3.4 \text{ Mpc}$.

that if the inclination is taken as a free parameter, a mean inclination of 25° would yield a circular velocity of $\sim 60 \text{ km s}^{-1}$ at $R = 7 \text{ kpc}$. Since the uncertainty in the inclination for this galaxy is about 10° (Oh et al. 2011), the MOND rotation curve would be consistent with the observed curve only if the inclination is fine-tuned to very unlikely values. For rings at $R > 12 \text{ kpc}$, Bureau & Carignan (2002) required inclinations of $i = 84^\circ$. Even in the worst scenario that the uncertainty in the inclination is of 30° , the rotation speed at $R > 12 \text{ kpc}$ would increase by a factor of $\sin(84^\circ)/\sin(54^\circ) = 1.25$ (from $\sim 40 \text{ km s}^{-1}$ to $\sim 50 \text{ km s}^{-1}$), which is not enough to reconcile MOND with observations (see Fig. 3).

5. CONCLUSIONS

van der Kruit (1995) noticed that the galaxies NGC 891 and NGC 7814 present very similar H I kinematics but remarkably different light distributions and claimed that this observation weakens the appeal of MOND. Here we present two galaxies that rotate at similar velocities but their baryonic masses differ by a factor of 5. We have shown that the rotation curve of HoII is not compatible with MOND unless the inclination is fine-tuned to a very unlikely value. This inclination is the one required for

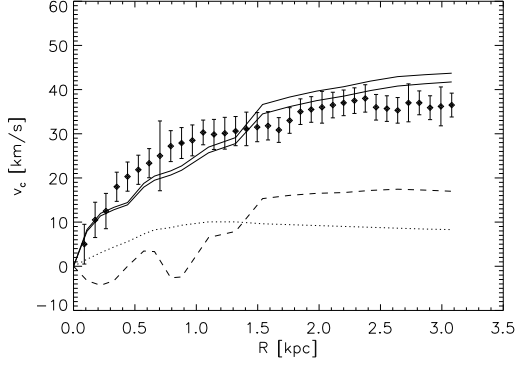


FIG. 4.— HoII rotation curve in MOND adopting the standard μ -function with $a_0 = 0.9 \times 10^{-8} \text{ cm s}^{-2}$ and a distance to the galaxy of 1.5 Mpc, a factor 2.3 closer than the nominal distance. The key to lines is the same as in Fig. 2.

HoII to satisfy the baryonic Tully-Fisher relation.

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